Wind tunnel experiment of drag of isolated tree models in surface boundary layer

GUAN De-xin (关德新)*, ZHU Ting-yao (朱廷曜), HAN Shi-jie (韩士杰)

(Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110015, P.R. China)

Abstract: For very sparse tree land individual tree was the basic element of interaction between atmosphere and the surface. Drag of isolated tree was preliminary aerodynamic index for analyzing the atmospheric boundary layer of this kind of surface. A simple pendulum method was designed and carried out in wind tunnel to measure drag of isolated tree models according to balance law of moment of force. The method was easy to conduct and with small error. The results showed that the drag and drag coefficient of isolated tree increased with decreasing of its permeability or porosity. Relationship between drag coefficient and permeability of isolated tree empirically was expressed by quadric curve.

Key words: Drag of isolated tree; Wind tunnel experiments; Pendulum method

CLC number: S711 **Document code:** A **Article ID:** 1007-662X(2000)03-0156-05

Introduction

Research on the interaction between vegetative surface and atmosphere is one of the aims of atmospheric boundary layer meteorology. Momentum transfer between the atmosphere and vegetative structure is a function of the physical attributes of the structure and the wind field (Grant 1985) drag of vegetation is an important index of the function.

There are various vegetative structures in surface, natural or planted or mix of them. Homogeneously dense vegetation may be the simplest surface in structure. Its drag was studied in many papers (e.g.Thom 1971; Raupach 1979; Bosveld 1997). Another structure of frequently researched was shelterbelt or windbreak, as it was widely constructed to reduce soil evaporation or wind speed in arid or windy areas, Its drag also was evaluated in many studies (e.g. Hagen 1971; Seginer 1975; Takahashi 1978; Wilson 1997; Zhou 1994; Zhu 1992; Guan 1995, 1996, 1998). Homogeneously dense vegetation was considered entirely as rough surface and shelterbelt or windbreak was looked as porous obstacle belt. Feature of individual tree was not taken into account in the studies.

Scattered or sparse trees is often seen a kind of surface, such as savannah, agroforest, parks and so on. Individual trees can be taken as elements of interaction between atmosphere and surface. Evaluated theoretical models of boundary layer parameters of this kind of surface (Raupach 1992, 1995) need the drag of isolated tree as an input index. Some previous studies dealt with individual tree (e.g. Mayhead 1973) or organs (e.g. Grant 1985; Vogel 1989; Holland 1991). But the measurements in the studies had few replications, thus permitted no reasonable extrapolation of the results to other kind trees.

This study is an attempt at measuring drag of isolated tree model in wind tunnel and describes the relationship between drag of isolated tree and its structural index.

Optical porosity and aerodynamic porosity of isolated tree

Two parameters, optical porosity and aerodynamic porosity, are introduced to describe the geometric characteristic and aerodynamics of isolated tree. The definition of the parameters and relationship between them were expounded in another paper (Guan and Zhu 2000).

Wind tunnel experiments on drag of isolated tree models

Wind tunnel and tree models

A simple wind tunnel of blow down type was made for the experiments. The length of test section is 10.0 m, width is 0.8 m, and height is 0.6 m. A honeycomb and 4 wire screens were installed at the upstream tunnel entrance to diminish flow rotation and large scale eddying. It is capable of generating a maximum air velocity of 8.0 m/s in the test section. Wind veloc-

---

Foundation item: This paper was supported by Chinese Academy of Sciences.

Biography: *GUAN De-xin (1962-), male, Ph. Doctor, assistant research fellow of Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110015, P. R. China.

Received date: 2000-05-15

Responsible editor: Song Funan

ity probe (probe of hot bulb anemometer) inserted through the holes open in tunnel ceiling and changed the height of measuring position. Three spires (40 cm height) were placed at upstream and grits (average diameter 3 mm) were uniformly spread on tunnel floor to product thick boundary layer. Measurements were carried out at the test section near exit where the boundary layer thickness was 14-16 cm and the roughness length was 0.018 mm (S.D.=0.006 mm).

A tree model was consisted of crown elements (plastic bunches) and trunk (iron wire), which string the element. Three kinds of elements were used to construct tree models. The crown became dense or porous as the elements increase or decrease. All models were designed in 8 cm height. 10 kinds of trees were combined with different figures. Solid tree model was substituted by wood cylinder. Structural characteristics were described in another paper (Guan and Zhu 2000).

The experiment description

Because no instruments were available for measuring so small drag of the tree models, the pendulum method was designed to the experiment (Fig.1). The ceiling at the exit of the wind tunnel was opened a long hole (1 cm×10 cm) along the wind direction. A pendulum was designed whose rigid arm was freely suspended just into the hole and didn't touch the ceiling board. The parallel double hooks at upper end of the arm hooked on a triangle section beam horizontally were fixed at steel frame above tunnel ceiling. And the up ridge of the fixed beam was sharply polished to decrease the friction with the hook as the pendulum vacillated. The double hooks controlled the arm only moving along the hole (wind direction). The down end of the arm is apart from the wind tunnel floor about 8 cm (height of the tree models) when it freely suspended. On tunnel floor just down the arm a ruler was drawn. A steel needle fixed at the down end of the arm as indicator. When the arm vacillated with the wind the indicator indicated the displacement of the arm end. The arm moved back and forth even in uniform wind. So a detention device installed out of the wind tunnel to detain the vibration of the arm. The device extended a detention arm into the tunnel to stop the pendulum arm upward.

In the experiment the position of the end of pendulum arm was read first in still air. Then the uniform-velocity wind flow was generated and detention arm was gradually regulated out of the tunnel to the optimum position that the pendulum arm was slightly bumping on the detention arm. The displacement of the end of pendulum arm was read. After stopping the flow the position of the end of pendulum arm in still air was read again to test the pendulum arm whether back to the initial position.

Then the needle was detached from the arm and fixed to the trunk base of the tree model also as indicator of displacement. And the tree model fixed to down end of the pendulum arm and maintained the trunk base departing from the tunnel floor about 1mm. The measuring process repeatedly described above and displacement was recorded. The atmospheric pressure and air temperature also were recorded as the experiment going on. The weight of pendulum arm, tree models and the needle were weighing.

In order to control the displacement of pendulum arm end in small scale, the more weight pendulum arm was selected, as the wind was stranger. This could diminish the errors that generated from much dip and elevation of the tree model. In the experiments the length of pendulum arm was 160 cm and the displacement of pendulum arm end was less than 7.2 cm, so the swing angle was less than 2.6°

Calculation of the drag of tree model

The force diagram of the pendulum system was also shown in Fig.1. When no tree model attached, the pendulum arm was forced by

(1) Gravity G_L. Its center was at the middle point O of the arm.

(2) Drag F_L. Its center was at the point M_L of the arm. And the dip angle was α_L and down end displacement was d_L.

The diameter of needle was 0.2 mm, only 1/40 of that of the pendulum arm. So the gravity and drag of the needle were neglected as they much smaller than that of the pendulum arm. When the pendulum balanced, the equation of moment of force was

$$G_L|OA|\sin\alpha_L = F_L|OM_L|\cos\alpha_L \tag{1}$$

Then

$$F_L|OM_L| = G_L|OA|\tan\alpha_L \tag{2}$$

As tree model fixed, the pendulum system was forced by

(1) Gravity of pendulum arm G_L;

(2) Drag of pendulum arm F_L'. It's center was at the point M_L' of the arm. The influence of the attached tree model on the flow forcing on pendulum arm was so small and the difference between angle α_L and α_T were also so small that follow equations could be truth approximately

$$F_L' = F_L \tag{3}$$

$$|OM_L| = |OM_L'| \tag{4}$$

and

$$F_L|OM_L| = F_L'|OM_L'| = G_L|OA|\tan\alpha_L \qquad (5)$$

(3) Gravity of tree model G_T. Its center was at middle point M_0 of the model.

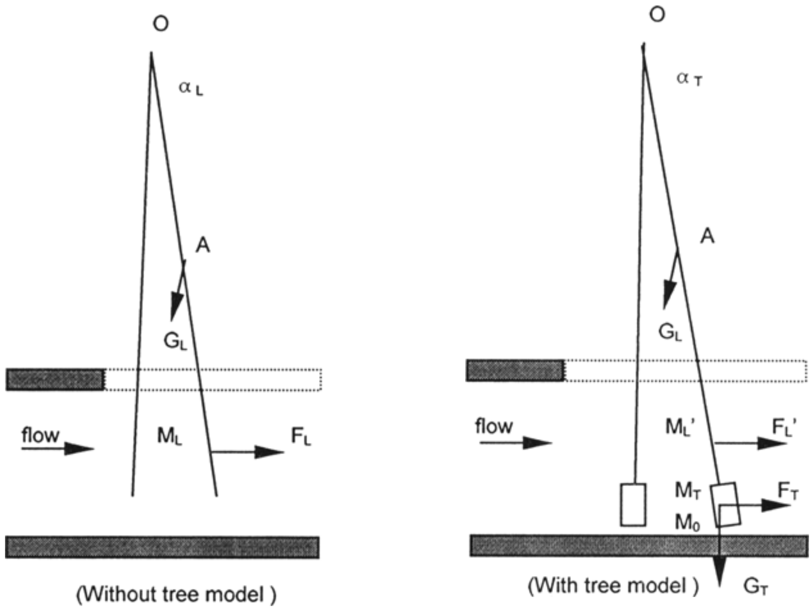

Fig. 1. Force diagram of the pendulum system (Swing angles were exaggerated)

(4) Drag of tree model F_T. Its center M_T was related to the vertical distribution of permeability of the tree. If the permeability was uniformly distributed, the height of point M_T could be estimated by follow (in neutral stratification)

$$H_T = \frac{1}{H}\int_{z_0}^{H}\frac{1}{2}\rho\left(\frac{u_*}{\kappa}\ln\frac{z}{z_0}\right)^2\alpha dz =$$

$$\frac{\alpha u_*}{2\kappa^2}\left[(\ln\frac{H}{z_0})^2 - 2\ln\frac{H}{z_0} + 2 - \frac{2}{H}\right] \qquad (6)$$

where μ_*, z_0 and κ were friction velocity of approaching flow, roughness length of the floor and Karman constant, so $|OM_T|=2|OA|+(H-H_T)$.

The balance equation of moment of force was:

$$G_L|OA|\sin\alpha_T + G_T(2|OA|+0.5H)\sin\alpha_T =$$

$$F_L'|OM_L'|\cos\alpha_T + F_T|OM_T|\cos\alpha_T \qquad (7)$$

Considering (5), then

$$F_T = (G_L|OA|\sin\alpha_T + G_T(2|OA|+0.5H)\sin\alpha_T -$$

$$G_L|OA|\tan\alpha_L\cos\alpha_T)/(|OM_T|\cos\alpha_T) \qquad (8)$$

All the terms in the right hand were measurable. So the drag of tree model F_T was easy to calculate.

Error analyses of the experiment

Errors could be caused probably from follow:

(1) Displacement reading: the longer as the displacement was, the bigger the reading error was. It was generally about 1 mm. The average displacement was about 4 cm and the relative average reading error was about 2.5%.

(2) Suspending of the tree model: the gap between trunk base and the tunnel floor was about 1 mm. This corresponded to omit 1 mm high trunk base. Wind velocity here was very low and the omission impacted little of drag (only 10^{-4} of the drag). So the suspending errors could be neglected.

(3) Dip and elevation of the tree model: the maximum elevation of the model in the experiment was 0.15 cm, corresponding to 2% of the model height. This caused the errors of drag about 2%. The maximum dip angle of the model was 2.6°. This may be neglected comparing with the dip of actual tree.

Results and discussion

Drag of isolated tree model

The measuring result showed in Fig.2. It shown that drag of isolated tree model was related to its permeability (or porosity) and approaching wind velocity. Less permeability and stranger wind velocity generated bigger drag. But the drag of cylinder model was less than that of expected.

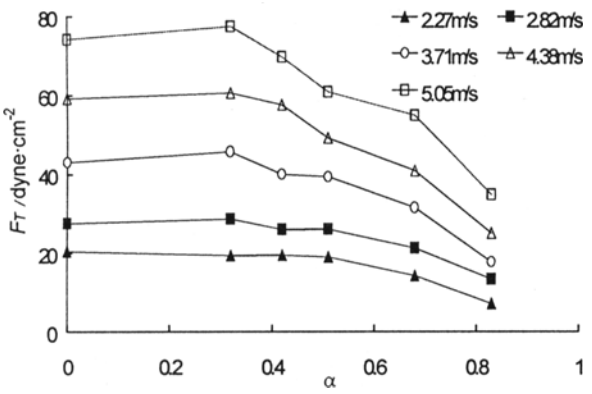

Fig. 2. Variation of drag of isolated tree F_T with permeability α under different approaching wind velocity at tree height

Drag coefficient of isolated tree model

Drag coefficient of isolated tree mode was defined as

$$C_T = 2F_T / (DH\rho u_e^2) \qquad (9)$$

where F_T and C_T were drag and drag coefficient of isolated tree respectively. D and H were the crown width and height of the tree. ρ was air density. u_e was geometrical mean wind velocity of the flow

$$u_e = \frac{1}{H}\int_{z_0}^{H}\frac{u_*}{\kappa}\ln\frac{z}{z_0}dz \approx \frac{u_*}{\kappa}\ln\frac{H}{ez_0} \qquad (10)$$

Fig.3 showed the variation of drag coefficient of

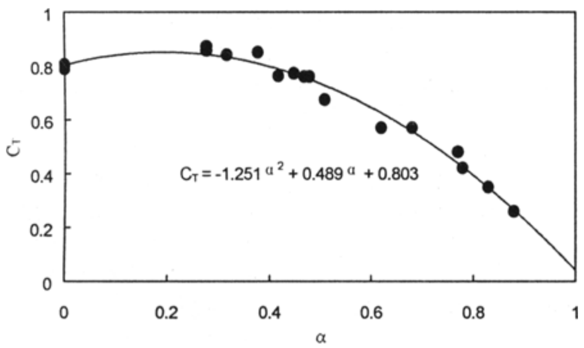

Fig. 3. Relationship between drag coefficient C_T and permeability α of isolated tree (dots were measurements and line was the empirical model)

isolated tree versus its permeability. Except for cylinder model, the drag increased with decrease of the permeability. Cylinder model had a slight small drag coefficient compared to dense tree model. This were caused by the attribute of cylinder model. It had smoother surface than that of tree model. And the friction with the flow was less. The relationship between drag coefficient of isolated tree and its permeability was empirically described by equation

$$C_T = -1.251\alpha_T^2 + 0.489\alpha_T + 0.803 \qquad (11)$$

with correlation R^2=0.981.

Conclusions

As the single tree was the basic element of interaction between atmosphere and some representative surface such as Savannah, agroforest and so on, drag of isolated tree was an important index for the aerodynamic research of these surfaces.

Because no instruments were available for measuring so small drag of the tree models in wind tunnel. The pendulum method was designed, and drag of the isolated tree model could be calculated by the formula evaluated from balance equation of moment of force. The experiment was easy to conduct and the errors were small.

The results showed that besides the crown scale, drag of isolated tree increased with decrease of its permeability or porosity. The drag increased as approaching wind became stronger. Drag coefficient of isolated tree decreased as its permeability increased. This relation empirically described by quadric curve.

This paper gave the results obtained from wind tunnel experiments. The tree models were relatively ideally constructed and in some extent, were different from actual trees in geometry and physical attributes. So the drag measurements of actual trees in field are expected. Nevertheless, the results in this paper gave the basic law about drag of isolated tree and will helpful for further researches.

References

Bosveld, F.C.1997. Derivation of flux from profiles over a moderately homogeneous forest [J]. Boundary Layer Meteorology, **84**: 289-327.

Grant, R.H. 1985. The influences of the physical attributes of a spruce shoot on momentum transfer [J]. Agricultural and Forest Meteorology, **36**: 7-18.

Guan Dexin *et al.* 1995. Experimental study on the relationship between windbreak drag and its section form [J]. Ecological Magazine, **14**(5): 15-19.

Guan Dexin *et al.* 1996. Theoretical and experimental study on drag partition of multi-row windbreak [J]. Chines Journal of Applied Ecology, **7**(2): 129-133.

Guan Dexin, Zhu Tingyao. 1998. Theoretical analysis of wind resisting ability of windbreak related to the structure [J]. Journal of Beijing Forestry University, **20**(4): 119-121.

Guan Dexin, Zhu Tingyao.2000. Wind tunnel experiments on canopy structural parameters of isolated tree and the leeward wind velocity field [J]. Chines Journal of Applied

Ecology, **11**(2): 202-204.

Hagen, E.J. *et al.* 1971. Windbreak drag as influenced by porosity [M]. Transactions of ASAE, p464-465.

Hidenori Takahashi. 1978. Wind tunnel test on the effect of width of windbreak on the wind speed distribution leeward [J]. J. Agr. Met., **33**(4):183-187.

Holland, M.R. *et al.* 1991. Momentum absorption by dried-pea crops: II. Wind tunnel measurements of drag on isolated leaves and pots [J]. Agricultural and Forest Meteorology, **54**: 81-93.

IDO Seginer. 1975. Atmospheric stability effect on windbreak shelter and drag [J]. Boundary Layer Meteorology, **8**: 383-400.

Mayhead, G.J. 1973. Some drag coefficients for British forest rees derived from wind tunnel studies [J]. Agricultural Meteorology, **12**:123-130.

Raupach, M.R. 1979. Anomalies in flux-gradient relationship over forest [J]. Boundary Layer Meteorology, **16**:467-486.

Taylor, P.A. 1988. Turbulent wakes in the atmospheric boundary layer. In: Flow and transport in the natural environment: Advances and applications. W.L. Steffen and T. Denmead (eds) [M], Springer-Verlag, Berlin, 270-292.

Thom, A.S. 1971. Momentum absorption by vegetation [J]. Q. J. Meteorol. Soc., **97**: 414 -428.

Vogel, S. 1989. Drag and reconfiguration of broad leaves in high winds [J]. J. Exp. Bot., **40**: 941-948.

Wilson, J.D. 1997. Afield study of the mean pressure about a windbreak [J]. Boundary Layer Meteorology, **85**:327-358.

Zhou Guangsheng *et al.* 1994. Theoretical relationship between windbreak drag and its permeability [J]. Chines Journal of Applied Ecology, **5**(1): 43-45.

Zhu Tingyao *et al.* 1992. Study on the relationship between drag of shelterbelts and their permeability [J]. Sciences of Forestry, **28**(6): 486-492.